STUDIES FOR STUDENTS[1]

THE RECENT ADVANCE IN SEISMOLOGY

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II. THE CO-ORDINATED "DISTANT" STUDY OF EARTHQUAKES

As already stated, in the first of these papers,[2] the one to whom we owe most for the exploitation of this new field for seismological study is Professor John Milne, whose later achievements crown a lifetime devoted to geophysical researches.[3] In 1883 he wrote: "It is not unlikely that every large earthquake might with proper appliances be recorded at any point on the land surface of the globe." Six years later the late von Rebeur-Paschwitz detected, in the photographic records of a very delicate horizontal pendulum, movements which he traced to earthquakes at a very great distance. These studies, published in 1895,[4] were thus the first to verify the prophetic

[1] Owing to the rapid development of the New Seismology, few treatises upon the subject have appeared. In addition to the briefer statements in Milne's *Seismology* (London, 1898) and Dutton's *Earthquakes* (London and New York, 1904), the student may with profit consult *Handbuch der Erdbebenkunde* by A. Sieberg, secretary of the German Chief Station for Earthquake Study at Strassburg. The subject will be more elaborately treated in Sieberg's *Geophysik*, soon to appear, and in *La science séismologique* by Count de Montessus de Ballore, which it is expected will also be issued during the present season. The most satisfactory treatment of the more strictly geological side of the subject of earthquakes is to be found in *Erdbebenkunde, die Methoden ihrer Beobachtung*, by Rudolph Hoernes (Leipzig, 1893).

[2] *Journal of Geology*, Vol. XV, pp. 288–97.

[3] John Milne, "Seismological Observations and Earth Physics," *Geographical Journal*, London, Vol. XXI (1903), pp. 1–25, map.

[4] E. von Rebeur-Paschwitz, "Europäische Beobachtungen des grossen japanischen Erdbebens vom 22. März 1894, und des venezuelanischen Erdbebens vom 28. April 1894, nebst Untersuchungen über die Fortpflanzungsgeschwindigkeit dieser Erdbeben," *Petermann's Mitteilungen*, Vol. XLI (1895), pp. 13–21, 39–42. (See also *Beiträge zur Geophysik*, Vol. II.)

words of Milne uttered twelve years earlier.[1] Today seismologists have so perfected recording instruments that at all first-class stations they are able to report great earthquakes which have occurred anywhere upon the globe, and less than a half-hour after their occurrence, the news having been telegraphed to them by the earth itself through, it may be, its entire diameter; and to have their reports confirmed by the telegraphic cables some hours or days later, according as cables have or have not been fractured. In his observing-station at Shide, upon the Isle of Wight, Professor Milne has been able to reassure anxious friends after the press announcement of a terrible earthquake in a nearly antipodal region, and confirm the fact from later press dispatches that the earlier report was a fabrication.[2]

The possibility of fixing the location of the disturbed region in the case of one of these so-called "unfelt quakes" is inherent in the fact that the waves of macroseisms are transmitted apparently not only through the mass of the globe, but also along its circumference. Those waves which first reach the station, the "preliminary tremors" of the seismogram (see Fig. 1), appear to come by the direct route through the earth's mass, as is pretty clearly shown by their constancy of velocity when the station is distant, and their variability of speed when the disturbed district is near. For the long distances the velocity is quite uniform and about 10 kilometers per second, so that the diameter of the earth is traversed in about 20 minutes.

The Japanese school of seismologists have generally held that the waves which produce these preliminary tremors in the seismogram

[1] An excellent account of the growth of the new methods of study may be found in the paper by W. Schlüter, "Schwingungsart und Weg der Erdbebenwellen," *Beiträge zur Geophysik*, Vol. V (1901), pp. 314–59.

[2] For a description of modern seismographs see C. E. Dutton, *Earthquakes in the Light of the New Seismology* (London and New York, 1904), in which the Italian instruments designed by Agemennone are described with especial fulness; C. F. Marvin, "The Omori Seismograph at the Weather Bureau" (*Monthly Weather Review*, June, 1903, pp. 1–8) and "Improvements in Seismographs with Mechanical Registration" (*ibid.*, May, 1906, pp. 1–6), where the Borsch-Omori instruments with Marvin's excellent improvements are described; A. Sieberg, *Handbuch der Erdbebenkunde* (Braunschweig, 1904), where the Wiechert Astatic Seismometer, the most modern and satisfactory instrument, though the most difficult to manage, is described and figured. Much may be learned from the trade catalogues of Spindler & Hoyer, of Göttingen, the manufacturers of the Wiechert instrument, and of J. &. A. Borsch, 15 Münstergasse, Strassburg, the European manufacturers of the Omori type of pendulum.

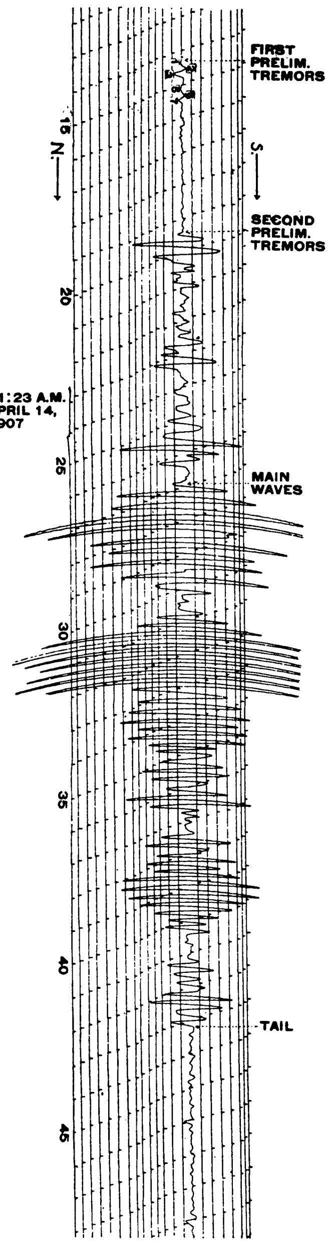

FIG. 1.—Record of the north-south component of the wave-motion rom the earthquake in Mexico of April 15, 1907, as registered on a Bosch-Omori horizontal pendulum at the U. S. Weather Bureau in Washington, D. C. (By courtesy of Professor C. F. Marvin.) The beginnings of the first and second preliminary tremors and of the main waves have been indicated. The intervals are minutes.

have an arcual path similar to, but deeper than, the "large waves," which follow them in time and are, as all agree, surface waves.[1] The velocity of these first waves, reckoned on this basis, would be about 14 kilometers per second instead of 10. Perhaps the strongest argument against this view is found in the known constants of surface rocks, which do not permit such a velocity. (See below, p. 400.)

It seems likely that the value assigned for the velocity of the direct waves may be subsequently considerably modified, since it has been largely based upon the records of the light Milne pendulums. Some sacrifice the pioneer must always make, and the standard Milne instrument suffers in comparison with the later German, Japanese, and Italian types, not only because of its lightness, but because the expense of photographic paper has necessitated a slow movement of the feeding-drum and a resulting contracted scale of the diagram. At the Batavia station a Milne and a Rebeur instrument have been installed side by side, and a comparison of the records now shows for the first time that the registration of shocks begins from one to ten minutes earlier upon the Rebeur pendulum.[2] The "preliminary tremors" of the Milne instrument may belong in the second phase of the records from more sensitive instruments.

For origins less than 1,000 kilometers distant such tremors do not appear in the seismogram, and it is supposed that they are combined with the large waves and reach the station at a speed of about 3.3 kilometers per second, with little doubt because of the lower rock densities which are traversed along the shorter and hence "crustal" chords.

The Earthquake Investigation Committee of Japan in 1894 instituted, at the suggestion of Professors Sekiya and Omori, a system of triangulation involving the use of four stations provided with exactly similar instruments and connected by telegraph to convey uniform ticks from a chromometer. The distances between the stations varied from 2.29 to 10.86 kilometers. All instruments being started by the same earthquake, the recognition of special marked vibrations

[1] Baron Dairoku Kikuchi, "Recent Seismological Investigations in Japan," *Pub. E.I. C.* (Foreign Languages), No. 19, 1904, p. 61.

[2] E. Rudolph, "Ostasiatischer Erdbebenkatalog" (1904), *Gerland's Beiträge zur Geophysik*, Vol. VIII, 1906 (1907), pp. 113–217.

allowed the times of arrival of the same shocks to be compared. The result obtained for the velocity of the surface waves of large amplitude (Section 5) was 3.3 kilometers per second, or the same as by the usual method.

It is a general observation that shocks are more violent at the earth's surface than they are in mines. At Przibram, in Bohemia, two similar modern Wiechert astatic pendulums have been installed, the one at the surface of the ground and the other in a mine 1,150 meters (or about 3,700 feet) under ground. The falling-off in amplitude of the shocks at the lower station is confirmed, but otherwise the seismograms appear to be nearly identical.

A most important study, and almost unique within its field, has been made by Nagaoka[1] upon the elastic constants of rocks. From his results he has obtained the velocity of propagation for waves in rock material, and these correspond fairly well with those actually measured by seismometers at the time of earthquakes.

The velocity of propagation of plane longitudinal waves within an infinite medium of steel is 6.2 kilometers per second. Within the earth's crust it is hardly to be expected that constant velocities will be obtained, since the crust is not homogeneous, and, further, is not isotropic, but quasi-crystalline. Several of the rocks investigated gave values for velocity as high as 6 and 7 kilometers per second. Nagaoka shows that a relation exists between the density and the elastic constant. In passing from Cenozoic to Archean rocks, with an increase of density from 2 to 3, the modulus of elasticity increased more than ten times in certain specimens. The mean earth density is 5.5+, and Nagaoka argues for a stratum of this density quite near to the surface. His studies have since been continued by Kusakabe,[2] using improved apparatus. For the velocity of propagation of waves in various types of Archean rocks Kusakabe

[1] H. Nagaoka, "Elastic Constants of Rocks and the Velocity of Seismic Waves," *Publications of the Earthquake Investigation Committee in Foreign Languages*, No. 4 (Tokyo, 1900), pp. 47–67.

[2] S. Kusakabe, "Modulus of Rigidity of Rocks and Hysteresis Function," *Journal of the College of Science*, Imperial University, Tokyo, Vol. XIX (1904), pp. 1–40, 22 plates and 53 figures. See also by the same author "A Kinetic Measurement of the Modulus of Elasticity for 158 Specimens of Rocks and a Note on the Relation between the Kinetic and Static Moduli," *Pub. E. I. C.* (Foreign Languages), No. 22 B, 1906, pp. 27–49.

obtained the average value 2.54. The average of all the rocks tested is a value slightly less than that of the large or surface earthquake waves.

The apparently uniform velocity of propagation of elastic earthquake waves through the core of the earth is a revelation of the first order of magnitude, for it indicates for the earth a uniformity of composition, and, moreover, a rigidity equal to one and a half times that of the hardest steel. The preliminary tremors from the great Indian earthquake of 1897, as received at Rocca di Papa, had an estimated period of 0.5 to 0.8 of a second, while their amplitude was but a fraction of a millimeter.

Following the preliminary tremors from a macroseism,[1] the seismogram indicates a second phase of larger disturbances; after which come the "large waves," which in the case of the quake above mentioned had a complete period of 22 seconds, a length of 34 miles, and a rise and fall of no less than 20 inches. These waves appear, therefore, to travel like a slow swell along the earth's surface.

Another fact of great interest is that the large waves gain in period of vibration and lose amplitude the farther they travel, so that an experienced observer can roughly estimate the distance of the disturbed area from the period of vibration of the waves. With fairly uniform rates of propagation established for both the direct and the surface waves which originate at any distant origin, the difference in time between the arrival of the preliminary tremors and that of the large waves gives a further measure of the distance of the origin from the observing-station. For example, a distance of 80 degrees corresponds to a time interval separating first preliminary tremors and first large waves of about 35 minutes.

Láska has derived surprisingly simple formulas for fixing the distance of the seat of disturbance in the case of remote earthquakes.[2] If V_1 be the time in minutes of the beginning of the preliminary

[1] Great confusion exists because of the different uses of the terms "macroseism" and "microseism," as well as of the adjectives derived from them. The usage here is that of both Milne and de Montessus, which makes "macroseism" apply to the greater disturbance on the ground.

[2] W. Láska, "Ueber der Berechnung von Fernbeben," *Mittheilungen der Erdbeben-Kommission der k. Akademie der Wissenschaften zu Wien*, N. F., No. 14 (1903), pp. 1–13.

tremors, V_2 that of the second preliminary phase,[1] and B that of the main or large waves in the seismograph; and if Δ be the distance in megameters (1 megameter equals 1,000 kilometers), then

$$1+\Delta=V_2-V_1$$

and

$$3\Delta=B-V_1 .$$

Benndorf has proven by many determinations the correctness of these formulas,[2] which are known as "Láska's Rules," and which may be stated in simple form as follows:

1. *The duration of the first preliminary tremors in minutes, less one, is the distance of the seat of disturbance in megameters.*

2. *The duration of all preliminary vibrations in minutes, less one, is thrice the distance of the seat of disturbance in megameters.*

An illustration of the precision in the measurement of distance with unfelt quakes is given by Alfani, the director of the Ximeniana station at Florence, for the Indian earthquake of April, 1905,[3] the error in determining the distance being only 32 kilometers if the geographic center of the affected district be regarded as the starting-point of the shocks.

Omori, on the assumption that the velocity of the waves which produce the first preliminary tremors (over an arcual path) is 13.7 kilometers per second, and that the velocity of the second preliminary tremors is 7.2 kilometers per second, has deduced a formula for finding the time of occurrence of an earthquake from the observations at a distant station.[4]

His formula is

$$t_0 = t_1 - 1.165\, y_1$$

where t_0 is the time of occurrence of the earthquake, t_1 the commence-

[1] Laska finds that earthquakes less than 500 kilometers distant produce no second preliminary phase in the seismograph.

[2] H. Benndorf, "Ueber die Art der Fortpflanzung der Erdbebenwellen im Erdinnern," *Mitth. d. Erdbeben-Kom. d. k. Acad. d. Wiss. z. Wien*, N. F., No. 29 (1905), p. 19.

[3] P. G. Alfani, "Il terremoto d'India del 4 Aprile, 1905, e le registrazioni sismiche all' osservatorio Ximeniana di Firenze," *Rivista geografica Italiana*, Anno XII (1905), fasc. V, pp. 1–6.

[4] F. Omori, "On the Estimation of the Time of Occurrence at the Origin of a Distant Earthquake from the Duration of the First Preliminary Tremors Observed at Any Place," *Bull. E. I. C.*, Vol. I, No. 1 (1907), pp. 1–4.

ment time of the earthquake at the distant observing station, and y_1 the duration of the first preliminary tremors reckoned in seconds. The time is thus obtained through subtracting from the time when the record begins the duration in seconds of the first preliminary tremors after multiplying by the factor 1.165.

Careful analysis of earthquake records shows that the large waves may be further divided into four sections, designated the third, fourth, fifth, sixth, and sometimes additional sections of the seismogram (the two phases of the preliminary tremors being included in the numeration). The vibrations of the third section are few and slow, those of the fourth section are somewhat quicker and of very large amplitude, while those of section 5 are of much shorter period and of large amplitude. The durations of these different sections of the complete earthquake record are roughly equal to one another, the third and fourth sections being taken together. The amplitude is greatest in the fourth and fifth sections. The feeble vibrations which end the seismogram are called its "tail."

It has been rather generally held as a theoretic proposition that the direct waves which produce the preliminary tremors of the seismogram are longitudinal—that is, compressional—vibrations; whereas the "large" or "main" waves vibrate in the plane transverse to the line of propagation. A decisive experimental proof of the correctness of this view seems to have been happily furnished by the registration of the recent Kingston earthquake of January 14, 1907, by the seismograph of the U. S. Weather Bureau.[1] The two Borsch-Omori pendulums of the bureau are so placed as to record the north-south and the east-west components of the wave motion. Now it happens that the port at Kingston, which is something more than 1,400 miles distant from Washington, differs in longitude by only 15 minutes. For our purposes, therefore, Kingston may be considered as located upon the meridian of Washington. Practically *no preliminary tremors were registered in the east-west direction* at the time of the earthquake, though a very distinct series was recorded in the north-south direction. Notwithstanding this difference, the main waves appeared at practically the same instant in the two records, but

[1] C. F. Marvin, "The Kingston Earthquake," *Monthly Weather Review*, January 22, 1907, pp. 1–4.

the amplitude of the east-west component was about five times that of the north-south component.

The deep significance of these modern seismograms having been recognized, the necessity for co-ordinating the work of different observers at once became apparent; for, if the distance of an earthquake origin from three or more stations could be determined, its location could naturally be fixed with much greater precision and accuracy. Under the leadership of Milne, the British Association has secured the co-ordination of the work of some forty-five stations well distributed over the surface of the globe, where observations are made upon a uniform type of instrument. All reports are forwarded to a central committee of the association, which makes comparison, and once in six months issues a report that is mailed to all the stations for further study.

Japan, with its relatively small but widely extended territory, has at present, besides its *Central Meteorological Observatory* and the *Laboratory of the Seismological Institute of the Imperial University* (both at Tokyo), seventy-one local stations provided with seismographs, and 1,437 other stations scattered throughout Japan. The seventy-one stations of the higher class receive standard time by telegraph from the central station at Tokyo.

In Italy the *Central Office for Meteorology and Geodynamics*, directed by Professor Luigi Palazzo, co-ordinates the work of fifteen seismological stations of the first rank. For collecting information upon Italian earthquakes there are 150 regular correspondents well distributed through the peninsula and Sicily, and 650 other persons who have agreed to telegraph an immediate report to the central office when any earthquake shock has been perceived by them. Since 1895 the data thus collected have been regularly published in the *Bollettino della Società sismologica Italiana.*

Germany has established some twelve stations of the first rank, in addition to the head station at Strassburg, where may be found the highest development of instrumental refinement in earthquake study. Here have been held the international conferences upon earthquakes, and here was founded in 1903 the International Seismological Association. The organ of the association, the *Beiträge zur Geophysik*, is edited by Professor G. Gerland, the director of the station, from

which also the annual catalogue of seisms is regularly issued. The staff included Professors E. Rudolph, Dr. C. Mainke, and Mr. A. Sieberg, all highly trained seismologists. Germany is soon to inaugurate a system of co-ordinated distant stations, in which will be included Samoa, Kiao-chau, German East Africa, and the Bismarck Archipelago.

After Great Britain no nation has better opportunities for establishing a co-ordinated system of earthquake stations than the United States. Coming late into the field, it will not be required to make the sacrifices of the pioneer on account of earlier and cruder instruments, and its isolated outlying territory is admirably distributed for the purpose in view. With first-class stations and modern instruments at Washington, in New England, California, Alaska, Panama, Honolulu, Tutuila, Manila, Guam, Cuba, and Porto Rico, much might be accomplished to offset the minor rôle which the nation has thus far played in the great advance of seismology. At the last annual meeting of the American Association for the Advancement of Science, held in New York City in December, 1906, a committee of seismology composed of fifteen members was appointed, and at a meeting of this committee held in Washington almost upon the first anniversary of the great California earthquake, arrangements were made by which the United States Weather Bureau will make application to the next Congress for an appropriation to be used in inaugurating a co-ordinated series of earthquake stations well distributed throughout the country.

The great Indian earthquake of 1897 was the first macroseism upon the land to be studied both by co-ordinated distant stations and by geologists upon the ground.[1] The diagrams of the stations show that the waves traveled not only through but around the globe, thus furnishing a sort of parallel to the atmospheric wave started by the eruption of Krakatoa in 1883.

The seismograms of some earthquakes show more than one set of large waves, and these have been designated W_1, W_2, and W_3. The first mentioned appear to have reached the station by the nearest

[1] R. D. Oldham, "Report on the Great Earthquake of 12th June, 1897," *Memoirs of the Geological Survey of India*, Vol. XXIX (1899), chap. xv. The unfelt earthquake, pp. 227–56.

arcual route. The waves, W_2, are from the diminished amplitude, and the time of their arrival to be ascribed to vibrations transmitted in the opposite direction over the antipodes, while the waves W_3 are relatively feeble and the time of their arrival is about 3 hours, 31 minutes behind that of W_1, or that necessary for the waves of section 5 to make a complete circuit of the globe with a velocity of 3.3 kilometers per second. The seismogram of the Turkestan earthquake of August 2, 1902, indicates these waves W_2 and W_3 distinctly.[1] (see Plate IV).

Milne has recently drawn attention to the interesting fact that even in the case of lighter earthquakes, from which the energy is so dissipated that no record is obtained at the more distant stations, a distinct thickening of the lines from the pen of the instrument may be noted in the station located at the antipodes.[2] These "antipodean survivors" of the large waves in English home stations may be traced to earthquakes in New Zealand, and their survival at the antipodes only is to be ascribed to the cumulative effects of waves which converge from many great circle routes.

There is much that is yet only speculation regarding the nature of the waves registered by the new seismographs,[3] and some of the waves which have been indicated in the records of non-astatic pendulums have originated in the instruments themselves; but the value of the methods devised for locating the disturbed areas seems to have been established. This tendency of pendulums to vibrate in their natural period is now being corrected by automatic damping devices, with which a new epoch in the development of the science is opened.

In his paper above cited Milne has brought together the results already obtained in the location of macroseisms.[4] On the basis of 265 such quakes recorded between 1899 and 1903, twelve seismic regions have been located which are either beneath the ocean or include both sea and continental border. (See Figs. 1. and 3 of

[1] Kikuchi, *loc. cit.*, p. 68, Fig. 37.

[2] John Milne, "Recent Advances in Seismology" (Bakerian lecture), *Proceedings of the Royal Society*, Vol. LXXVII (1906), p. 373.

[3] See W. Schlüter, "Schwingungsart und Weg der Erdbebenwellen," *Beiträge zur Geophysik*, Vol. V (1901), pp. 358, 359.

[4] A later report has been issued with 462 quakes included (Seismological Committee of the British Association for the Advancement of Science). See Fig. 2.

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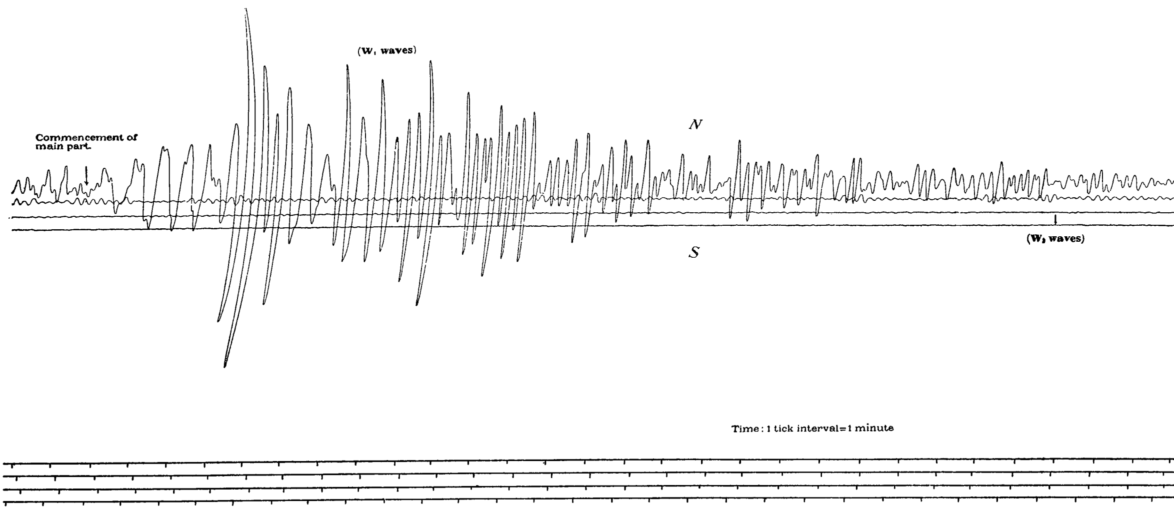
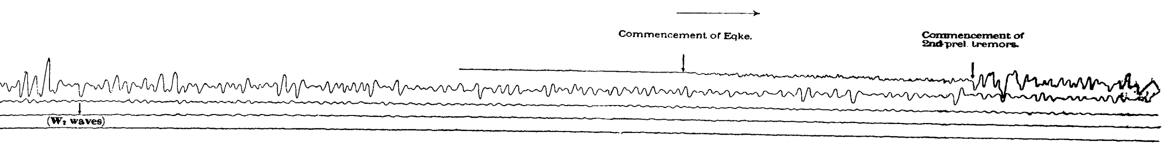
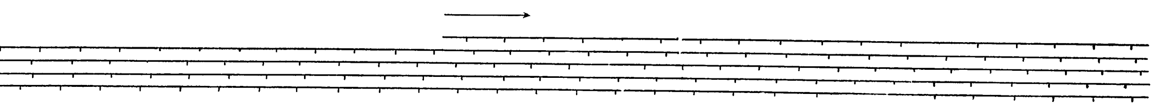


RECORD OF THE TURKESTAN EARTHQUAKE OF AUGUST





T 22, 1902, OBSERVED IN TOKYO. (AFTER KIKUCHI)

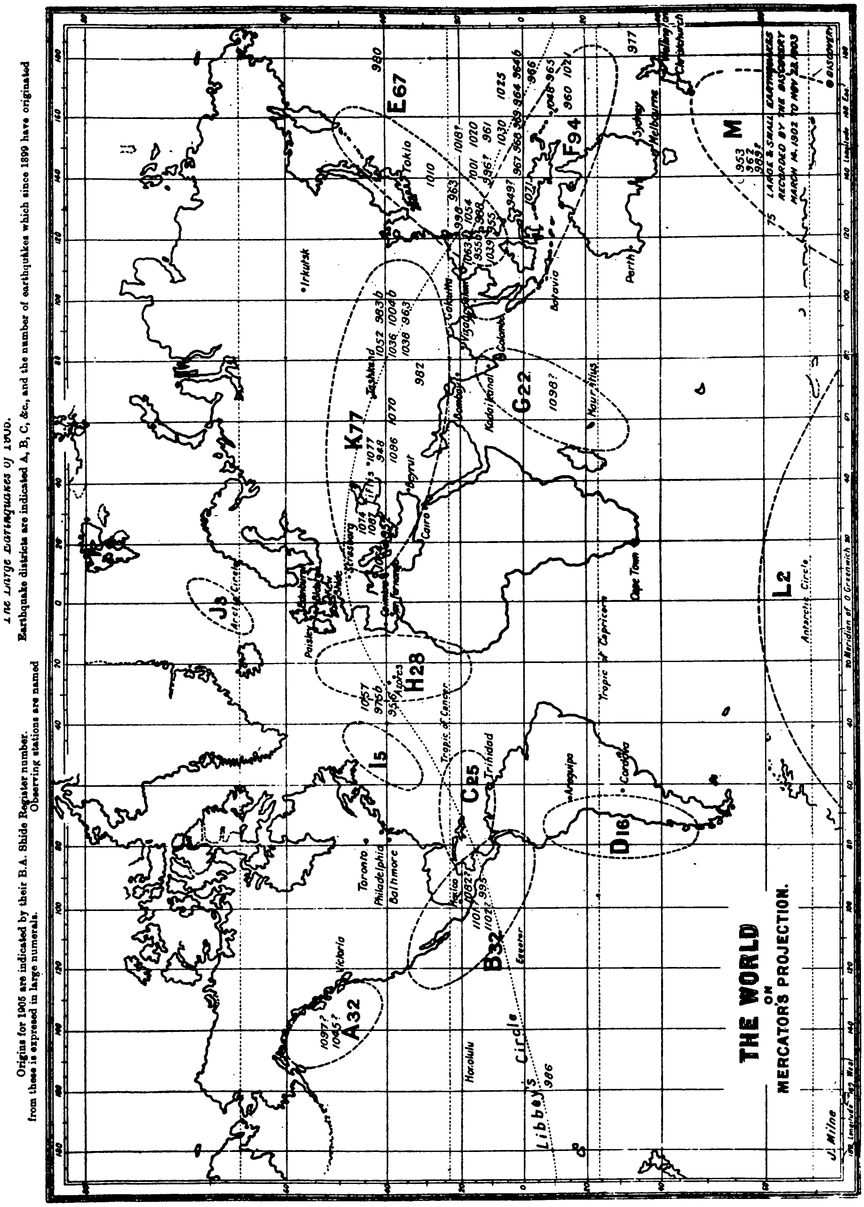


FIG. 2.—Map of earthquake "ovals," including the year 1905. (After Milne.)

the first paper of this series.) For the most part these are well-known earthquake regions, though the results have been criticized on the ground that certain well-known seismic regions, such as California, Andalusia, Lake Baikal, and New Zealand, are not indicated, while Newfoundland and the Indian Ocean are. As regards this objection, it should not be overlooked that regions of high seismicity may not necessarily be regions of equally frequent macroseisms, and the brief period that the method has been in operation removes much of the force of the objection so far as the seismic regions not indicated are cencerned. As regards Newfoundland, the "oval" of Milne merely grazes its corner and is centered over the steep wall of the ocean deep at the margin of the Great Banks. As this scarp is off the lane of transatlantic steamers, direct observation of submarine quakes should in any case be seldom made. We find, however that on September 27, 1838, the ship "La Claudine," Captain Blount, while in this vicinity (Lat. 31° 40′ N. and Long. 42° 10′ W.) experienced a most severe series of shocks which lasted three-quarters of an hour. Occurring in the night and in perfectly clear weather, everyone was aroused and rushed on deck believing the ship was going down. Nearly all the breaks in the Atlantic cables occur at this wall, and on October 4, 1884, the three cables running here in parallel lines, about ten miles apart, were simultaneously fractured at points opposite each other and in a straight line.

The other oval of macroseismic origins to which objection has been made is likewise seldom crossed by vessels except at its margins, but we have here the record that on October 13, 1863, a submarine quaking of great intensity, accompanied by rumbling like thunder, was felt by a vessel in Lat. 20° S. and Long 67° E. Other severe quakes have been felt by vessels near the margin of this oval on February 9, 1823, and on January 29, 1882. It seems likely, therefore, that the new method is extending our knowledge of earthquakes into regions of which we should otherwise have at best but little knowledge, and it confirms the generalization that much the greater number of movements within the crust occur beneath the sea and at the borders of the great ocean deeps. A map based upon a larger series of observations is reproduced after Milne in Fig. 2.[1] Milne's

[1] British Association, *Seventy-sixth Report* (York, 1906), Plate I.

earlier map displays in addition the ridges and deeps of the ocean floor, and he shows that there is a relationship between the distribution of origins of macroseisms and the pronounced irregularities of the relief; thus affording for the sea areas a complementary verification of de Montessus' conclusions.